V. Stochastic cooling

A. Introduction/overview

Beam cooling is a technique whereby the physical size and energy spread of a particle beam circulating in a storage ring is reduced without any accompanying beam loss. The goal is to compress the same number of particles into a beam of smaller size and energy spread, i.e. to increase the particle density. Phase space density can be used as a figure of merit for a particle beam, and cooling increases the density. One may ask how it is possible to increase the phase space density of a particle beam without violating Liouville's Theorem, which states that phase space volume is conserved. The answer is that Liouville's Theorem only applies to "conservative" systems. Cooling, by definition, is not a conservative process. The cooling electronics act on the beam through a feedback loop to alter the beam's momentum or transverse oscillations.

Two types of beam cooling have been demonstrated and used at various laboratories: electron cooling, which was pioneered by G. I. Budker, et. al., at Novosibirsk, and stochastic cooling, developed by Simon van der Meer of CERN. Electron cooling gets its name from the fact that an electron beam is used to cool the particles in question. Stochastic cooling is so named because of the stochastic nature of the beam – i.e., particles move at random with respect to one another.

Theoretically, electron cooling works on the principle of a heat exchanger. Two beams travel a certain distance parallel to each other: a 'warm' beam of protons, antiprotons, or heavy ions with relatively large variation in transverse kinetic energy and a 'cold' beam of electrons having much less variation in transverse kinetic energy. Both beams travel at approximately the same velocity and as the beams interact, the transverse kinetic energy of the warmer beam is transferred to the electron beam, which is then collected at the end of the cooling section.

Electron cooling was demonstrated at Fermilab in the early 1980's in a small storage ring known as the Cooling Ring which was located in a blue plywood racetrack-shaped building west of the Linac and Booster. It was on this machine, too, that stochastic cooling was first achieved in the western hemisphere.

During the designing of the Fermilab antiproton source, electron cooling was not the preferred choice due to the lack of proven high current electron sources. Since then, the technology has improved to the point that electron cooling is a viable alternative for future medium-energy storage rings. For that reason, electron cooling is being developed for use in the Recycler Ring. Since the Antiproton Source only employs stochastic cooling at this time, the remainder of this chapter will concentrate on this technique for beam cooling. The stochastic cooling systems used in the Antiproton Source are either betatron or momentum. Betatron, βtron and transverse all refer to systems that reduce betatron oscillations in the horizontal and vertical transverse planes. Similarly, momentum, longitudinal, dp, and Δp are used interchangeably to describe systems that reduce the momentum spread of the beam.

B. Fundamentals

The terms beam temperature and beam cooling have been borrowed from the kinetic theory of gases. Imagine a beam of particles circulating in a storage ring. Particles will oscillate around the beam center in much the same way that particles of a hot gas bounce back and forth between the walls of a container. The larger the amplitude of these oscillations in a beam, the larger the beam size. The mean square velocity spread is used to define the beam temperature in analogy to the temperature of the gas. Beam cooling is desirable for applications such as:

- Providing a low emittance beam to a collider ring in order to maximize collision rate (luminosity).
- Accumulation of rare particles – cooling to make space available so that more beam can be stacked into the same storage ring (e.g. the Accumulator).
- Preservation of beam quality – cooling to compensate for various mechanisms leading to growth of beam size and/or loss of stored particles; Tevatron bunched beam cooling was proposed for this reason, though the Tevatron lattice and bunched beam structure made it difficult to achieve.
- Improvement of interaction rate and resolution-cooling. To provide sharply collimated and highly mono-energetic beams for

precision experiments with colliding beams or beams interacting with targets such as E760 and E835 in the Accumulator.

Consider a single particle circulating in a storage ring as shown in the single particle model depicted in figure 5.1. Assume that the particle has been injected with some error in position and angle with respect to the ideal orbit (the center of the beam pipe). As the focusing system tries to restore the resultant deviation, the particle oscillates around the ideal orbit. These betatron oscillations can be approximated by a purely sinusoidal oscillation. The cooling system is designed to damp the amplitude of this oscillation. A pickup electrode senses the position of the particle on each traversal. The error signal is ideally a short bipolar pulse with an amplitude that is proportional to the particle's deviation at the pickup. The signal is amplified through an octave-band amplifier and applied to kicker electrodes which deflects the particle by an angle proportional to its error.

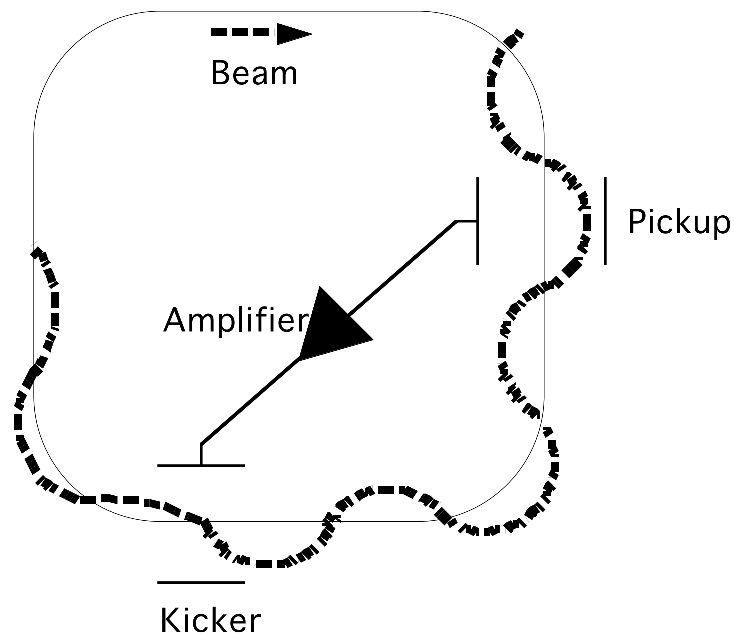
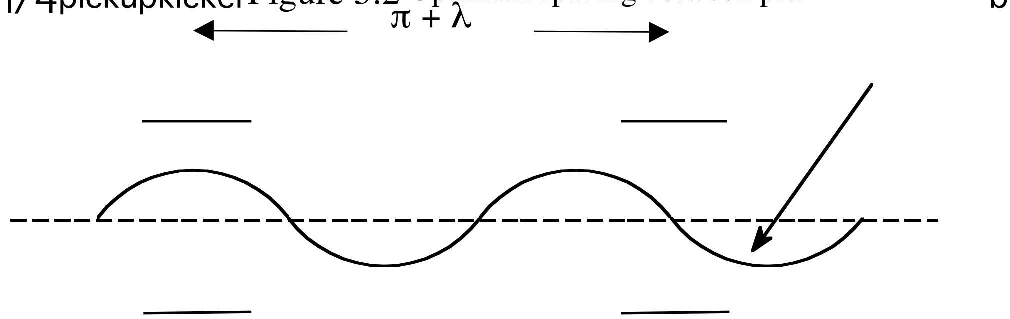


Figure 5.1 One-Particle Model for a Transverse Stochastic Cooling System

Specifically, consider a horizontal beam pickup that consists of two plates (usually parallel) and is sensitive to either horizontal motion or equivalently a dipole oscillation. The pickup is centered on the middle of the beam pipe, with one plate to the left of center and the other to the right. If the particle passes through the pickup off-center, the plate which the particle passes closest to will have a greater current induced on it. If the signals are combined by measuring the difference between them in a so-called 'delta' or Δ mode, the output will be a measure of the relative particle position with respect to the center of the beam pipe. Generally, the output of several sets of electrodes are combined in phase to provide a signal of usable amplitude compared to the inherent thermal noise signal. This signal is then amplified and applied with the most optimal averaged phase (timing) to the kickers. The kicker, because of the reciprocity theorem, is a similar arrangement of plates on which a transverse electromagnetic field is created which can deflect the particle.

n/4pickupkickerFigure 5.2 Optimum spacing between pickup and kicker



Since the pick-up detects a position error and the kicker provides a corrective angular kick, their distance apart is chosen to correspond to a quarter of a betatron oscillation (plus a multiple of π wavelengths if more distance is necessary). As shown in figure 5.2, a particle passing the pick-up at the crest of its oscillation will then cross the kicker with zero position error but with an angular deviation which is proportional to the displacement at the pick-up. Given a perfect kicker response and perfect betatron phasing, the trajectory of the particle would be corrected to that of the central orbit. A particle not crossing the pick-up at the crest of its oscillation would receive only a partial correction and require additional passages to eliminate the oscillation. Cooling systems in fact require many iterations to cool the beam due to the large number of particles involved and the finite bandwidth of the hardware.

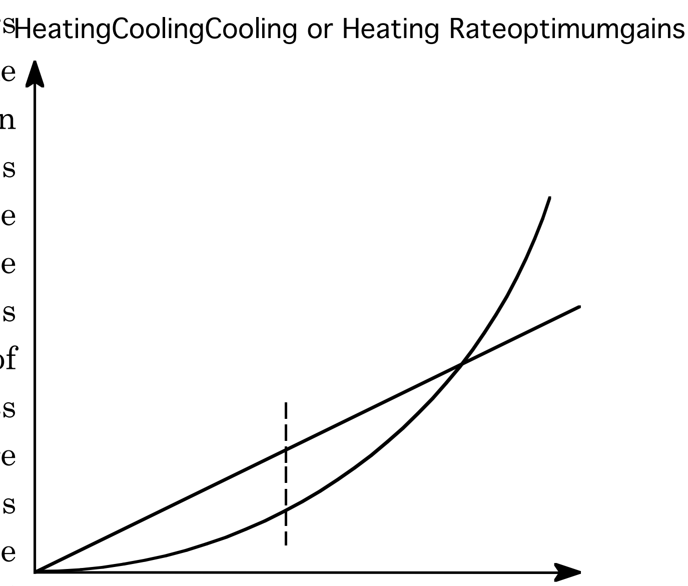
There is another important aspect of stochastic cooling that this model may explain: the correction signal has to arrive at the kicker at the same time as the particle for optimum cooling. Since the signal is delayed in the cables and the amplifier, whereas the particle is moving at close to the speed of light, the cooling path has to take a shortcut across the ring to reach the kicker at the correct time. For reasons explained below, applying the correction signal later than on the same revolution when it was created will lead to less efficient cooling or even heating.

Particle beams, of course, are not composed of just a single particle. Rather, a beam is a distribution of particles around the circumference of the storage ring. Each particle oscillates with a unique amplitude and random initial phase and in this model the cooling system acts on a sample of particles within the beam rather than on a single particle. The number of particles in a sample, N_S, is given by:

$$N_s = \frac{N}{(2WT)}$$

where N is the number of particles in the beam, W is the bandwidth of the cooling system, and T is the beam's transit time around the ring. Using one of the Debuncher systems as an example with N = 6 X 10^7 particles, W = 4 GHz (Debuncher systems operate at 4 to 8 GHz), and T = 1.695 μs yields $N_S \approx$ 4,425 particles within each equally spaced sample. Making the bandwidth sufficiently large would permit the single particle model above to be valid, but designing pickups and kickers with good response characteristics is technically extremely difficult.

The cooling process can be looked at as competition between two terms: (a) the coherent term which is generated by the single particle, and, (b) the incoherent term which results from disturbances to the single particle from its fellow sample members through the feedback loop. The coherent signal's contribution to the cooling process is linearly proportional to the system gain while the incoherent heating term is proportional to the square of the system gain. If one plots these two terms as in figure 5.3, it is shown that there is some point at which the cooling term is maximized against the heating term. This



is known as the optimum gain of the system. Note that this is usually different from the maximum gain of the system.

Mixing is a term used to represent how completely particles change position with respect to each other. Particles of different momenta "shear" away from each other due to path length differences as they traverse the ring. The stochastic cooling rate is maximized if an independent set of particles constitute each sample upon each revolution. This is sometimes referred to as "good" mixing. The term "stochastic cooling" is derived from the need for a random or stochastic sample of particles passing through the pickup upon each revolution for cooling to work effectively. Partially random samples are produced because each particle is on a slightly different orbit due to the momentum spread of the beam. The lattice parameter known as the "slip factor" also contributes to the rate at which the particle samples are mixed from turn to turn. If the samples contain mostly the same particles from turn to turn, then the cooling rate is decreased.

Although mixing of particles sampled at the pickup is beneficial, no mixing is desired between the pickup and the kicker. This is since the signal obtained at the pickup must be applied at the kicker to the sample creating the signal. Mixing between the pickup and kicker is sometimes referred to as "bad" mixing. An ideal cooling system would have no mixing between the pickup and kicker while having complete mixing between the kicker and the pickup. In reality, the mixing factor present in an accelerator is a compromise between these two extremes. The lattice of the ring in question and the momentum spread of the beam determine the mixing factor.

These factors can be written as an equation for the rate, $1/_{\text{cooling time}}$ or $1/_{\tau_{x^2}}$ (where τ is the cooling time constant), at which a beam is cooled:

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N}\left[2g\left(1 - \tilde{M}^{-2}\right) - g^2(M + U)\right]$$

where W is the bandwidth of the cooling system, N is the number of particles in the ring, g is the system "gain", or more accurately the number of particles multiplied by the electronic gain, $\tilde{M}$ is the ‘unwanted’ mixing factor, M is the ‘wanted’ mixing factor, and U accounts for random noise.

A list of selected references is included at the end of this chapter which form the basis for this text and which can provide much more information to the reader on the theoretical aspects of stochastic cooling.

C. Betatron cooling

Betatron or transverse cooling is applied to a beam to reduce its transverse size, i.e. to reduce its horizontal or vertical emittance. The single particle model of cooling described above was that of a simple betatron cooling system. Betatron cooling systems use differential pickups for generating the error signal. In the case of the antiproton source, both pickups and kickers are located in areas of low dispersion. This is so that any particles passing through the pickups off-center will have that position shift due only to transverse oscillations. In a high dispersion region, a particle's position could also be due to differences in momentum, and the resulting kicks could lead to unwanted momentum heating of the beam. A transverse field is applied to the particles by the kickers by applying the error signal to the kicker electrodes in "push-pull" fashion (one kicker plate has the same charge to push the beam, the opposing kicker plate has the opposite charge to pull the beam). Details of the specific transverse systems in the antiproton source are given below.

D. Momentum cooling

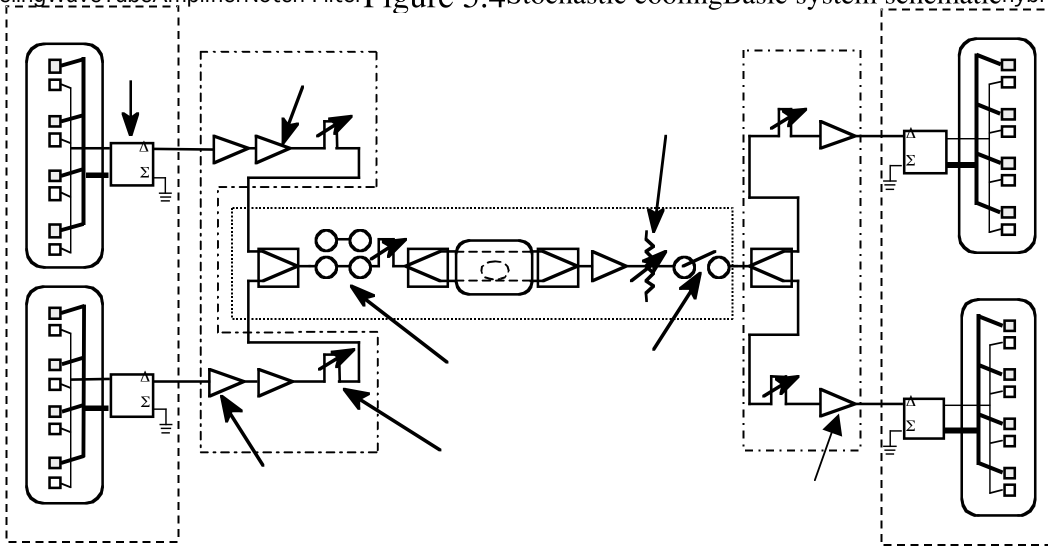
Momentum cooling systems reduce the longitudinal energy spread of a beam by accelerating or decelerating particles in the beam distribution towards a central momentum. In a momentum cooling system, the pickup signals are combined in sum mode and similarly, the signal applied to the kicker electrodes is also done in sum mode, providing longitudinal fields to accelerate or decelerate the passing particles.

Momentum cooling is used for several reasons in the Pbar source. Its function in the Debuncher is to further reduce the momentum spread of the beam (bunch rotation is the other mechanism used to reduce the momentum spread in the Debuncher). The stacktail momentum cooling system is used to push the antiprotons deposited by ARF-1 on the edge of the stacktail and decelerate the antiprotons towards the core. The function of the core momentum systems is to maintain a small momentum spread on the particles in the core. This is desirable for two reasons, first to keep particles from striking the Accumulator aperture and second to allow a denser bunch of antiprotons to be extracted during transfers. Accumulator momentum pickups are located in high dispersion areas and are positioned over the beam that is to be cooled (stacktail pickups over the stacktail, core pickups over the core). More details on each Δp system can be found in the following sections.

E. Specific systems

The stochastic cooling systems in the Debuncher and Accumulator are described below (use figure 5.4 as a reference). While each of the stochastic cooling systems perform different functions, they each have similar components which will be subdivided into six basic parts for this discussion:

TravelingWaveTubeAmplifierNotch FilterFigure 5.4Stochastic coolingBasic system schematichybridcryo



beam pickup electrodes: quarter-wave loop (directional coupler) pickups are contained within a tank assembly that is kept under vacuum. The pickup electrodes are striplines with a terminating resistor on the adjacent grounded walls of the tank. Figure 5.5 illustrates the electric field lines generated by the passage of charged particles. More accurately, each antiproton generates a short pulse in the stripline as it traverses the gaps. The pickup plates form transmission lines with a characteristic impedance. A series of pickup electrodes are housed in a pickup tank. Opposing electrodes (top and bottom, left and right, depending on the application) are combined in phase by combiner boards. Sum and difference signals are created by adding or subtracting signals between plates located on opposite sides of the vacuum chamber. Difference signals are used for betatron cooling; sum for momentum cooling. The sum and difference signals are created by passive devices known as hybrids.

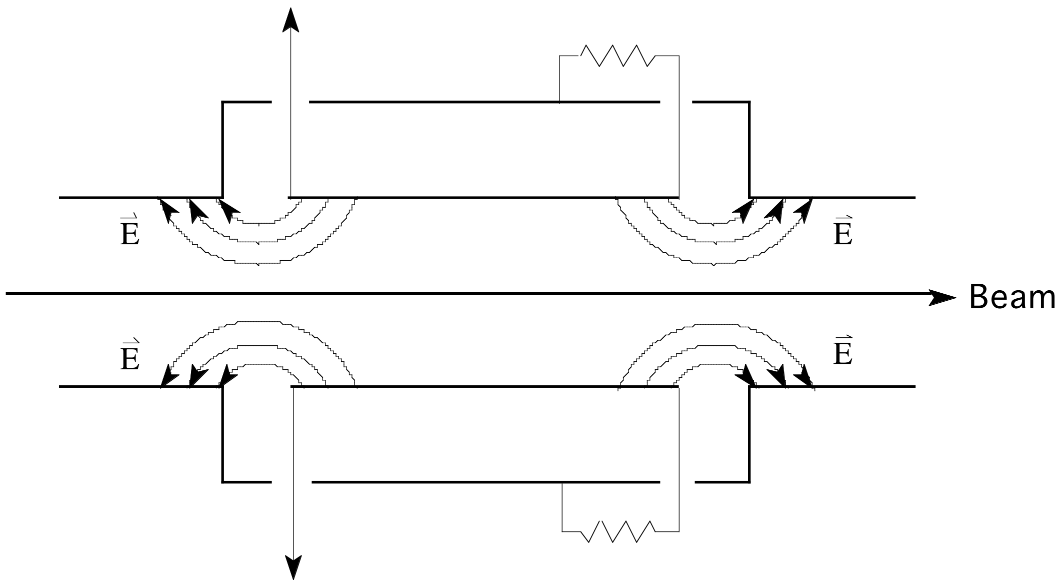


Figure 5.5 Pickup electrode

low level electronics: the resultant sum and difference information is amplified, then added in phase with information from other cooling tanks, if necessary, by means of mechanical delay lines known as trombones. The first stage of amplification is accomplished by GaAsFET preamplifiers, which in most cases are cryogenically cooled to reduce thermal noise. The Debuncher preamplifiers are cooled to liquid helium temperature, stacktail preamplifiers are cooled to liquid nitrogen temperature. Core systems do not require cryogenic cooling because there is a stronger signal from the beam. The 2-4 GHz core momentum system is the exception, the preamplifiers are cooled to liquid nitrogen temperature. Since the pickup tank is located in A60 along with the stacktail pickup tanks, there was little additional expense required to provide liquid nitrogen to preamplifiers. Ultimately, an amplified signal with a good signal to noise ratio is the input to the next level of the system.

medium level electronics: more amplification is applied and the signal is sent towards the kickers on a single coaxial cable known as a trunk line. Trombones are again used to ensure that the signal arrives at the kickers at the time that the sample of beam producing the signal on the pickups arrives at the kickers. Also included in the medium level electronics are variable PIN (Positive, Intrinsic, Negative: a type of semiconductor) attenuators which permit the gain of the system to be adjusted. Increasing the attenuation (expressed in units of db's) will lower the power output of the system.

Another kind of component found in this level are two varieties of switches. Transfer switches break the continuity between the pick up and kicker in order to make open loop transfer function measurements. The beam is a feedback element in this measurement. PIN switches are means of opening and closing the circuit. PIN switches are used because they are solid state devices that do not have mechanical fatigue problems from frequent cycling. Most PIN switches have gating capability: the switch can be turned on (the circuit is closed), off (the circuit is open), or gated (the switch can be automatically turned on and off via timers). The core systems, for example, are gated during beam transfers so that the cooling is turned off when the clock event that initiates unstacking occurs. It is turned back after the transfer has been completed.

An important component of many of the system's medium level circuitry are notch filters. Notch filters act to remove undesired components of the signal from the pickup before being applied to the kicker (in the case of the Accumulator stacktail and Debuncher betatron systems) or to shape the gain profile (as in the case of the Debuncher momentum system). Specific examples will be provided with the description of each cooling system below. Notch filters built for the cooling systems are of the correlator type, which use the constructive and destructive interference of the same signal transmitted over two transmission lines – like an interferometer. The basic components of the filters are a splitter, trombones, phase detectors and a hybrid. The splitter splits the medium level signal between two legs - a 'short' leg which is a straight ahead path for the incoming signal and a 'long' leg which consists of a low loss Bulk Acoustic Wave (BAW) delay line providing approximately one revolution period's worth of delay. Trombones and phase detectors are used to maintain the proper phase relationship between the two legs. A hybrid combines the two legs.

high level electronics: the signal is fanned out to all of the kicker tanks and unraveled in time as appropriate by means of splitters and trombones. Prior to being applied to the kicker electrodes, the signals are further amplified at microwave frequencies through devices known as Traveling Wave Tubes or TWTs. Although part of the high level, the TWTs are treated separately here.

Traveling Wave Tube: The TWT is a linear beam tube amplifier that provides 30-60 db of gain over octave bandwidths at microwave frequencies.

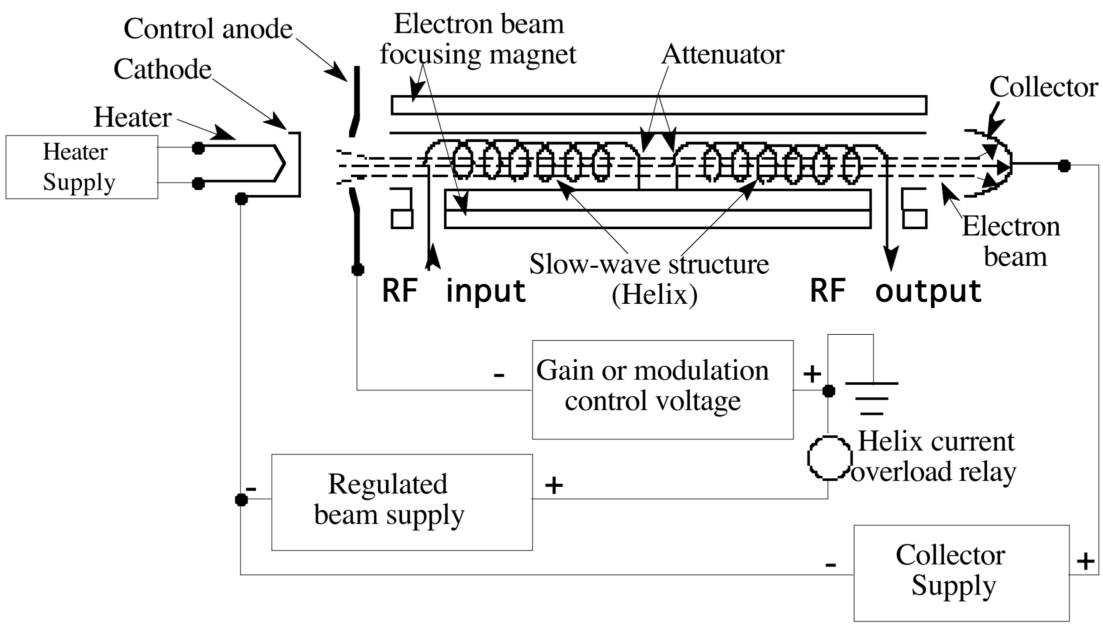


Figure 5.6 Helix type Traveling Wave Tube

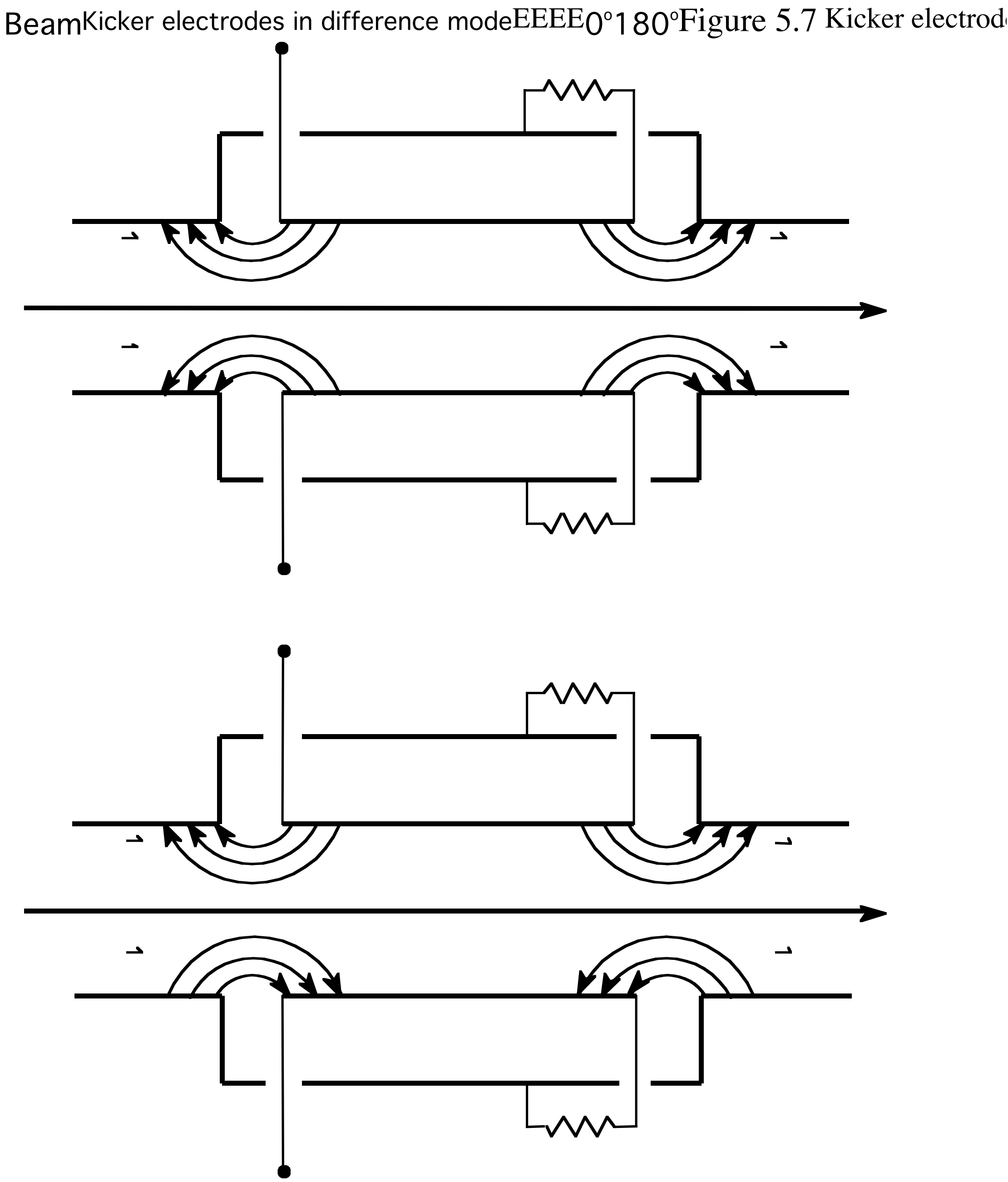
Power levels of a few watts to thousands of watts are attainable. The TWTs used in the antiproton source for stochastic cooling operate over octave bandwidths of 2-4 GHz and 4-8 GHz. Each has a saturated power level of 200 watts and 40-50 db of gain although they are normally run at 100 watts or less. Refer to figure 5.6, which diagrams a typical TWT, as you read the explanation that follows.

An electron beam is accelerated down the center of a helical 50 Ω transmission line with the helix power supply providing the source of acceleration voltage. The kinetic energy of the electron beam is typically 3-10 keV and beam currents in the 200-500 mA are produced from the TWTs used in the antiproton source. The microwave signal to be amplified is applied to the helical transmission line. Due to the relatively slow velocity of the electron beam, the helical transmission line acts as a "slow wave" structure forcing the propagating microwave signal to match the velocity of the electron beam. Adjustment of the helix supply is necessary to properly match the velocities and optimize tube performance. Propagating in "sync" causes a velocity modulation or bunching of the electron beam resulting in the electron beam imparting some of its energy to the latter part of the slow wave transmission line structure (i.e. gain).

The transmission line is not a resonant structure hence a TWT can have a wide bandwidth of operation. An attenuating material is used to support the helical structure to provide isolation between the input and output (if the attenuation material is omitted, it is a BWO or Backward Wave Oscillator). The entire slow wave structure, electron source (cathode) and collector are housed in a sealed stainless steel vacuum envelope. The beam is confined within the helix with permanent magnet focusing. Some higher power TWTs use powered solenoidal magnets, but those used in the antiproton source use rare earth magnets. The efficiency of TWTs is typically below 20% and those used for stochastic cooling in the antiproton source are about 10% efficient. The excess beam energy ends up in the collector. To improve efficiency, several stages of collector may be employed. While the stochastic cooling TWTs typically have one or two stages, some may have up to 4 collectors to improve efficiency. An anode may be added to the TWT to provide modulation or gain control. Only the 2-4 GHz TWTs at Fermilab have a modulation anode.

The power supplies for a TWT must be very well regulated to produce a stable electron beam. The propagation time through a TWT is approximately 10-15 nanoseconds while the stochastic cooling systems require timing precision to a few picoseconds. Voltage ripple of just a fraction of a percent is sufficient to cause enough propagation velocity variation in the electron beam to cause system timing problems.

kicker electrodes: physically the kicker electrodes are identical to their pickup counterparts. Each loop is terminated with a resistor and is rated to handle up to 10 Watts of microwave power. The stacktail and core kicker tanks in straight section 30 are outfitted with a design of array referred to as a planar loop as opposed to the original three-dimensional microstrip kicker design. Planar loops are made on printed circuit boards and are considered superior in terms of ease of fabrication and improved mechanical tolerances.



The kicker arrays and terminating resistors are cooled with water provided by a closed-loop system. Make-up water to the system comes from Pbar 95 LCW, but there are no deionizing cartridges used to preserve the low conductivity. The cooling water is usually referred to as “clean” water, and has excess heat removed by heat exchanging with 55 degree chilled water. Chilled water was originally used for cooling the tanks, but proved to be too dirty causing clogged flow turbines and reduced cooling efficiency

Although kicker electrodes for transverse and longitudinal cooling systems are physically the same, there is a difference in how the correction signals are applied to them. Simplified diagrams of kickers in both sum (longitudinal) and difference (transverse) modes are illustrated in Figure 5.7. As with pickup electrodes, excitation of the beam takes place at the gaps between the pickup and grounded wall. Again referring to Figure 5.7 note that in sum mode the signals applied to the kicker electrodes are in phase with each other. When in sum mode the electric fields are oriented so that a longitudinal kick is applied to the beam. In difference mode the signals are 180° out of phase with respect to each other and the electric fields result in a transverse kick to off-center particles.

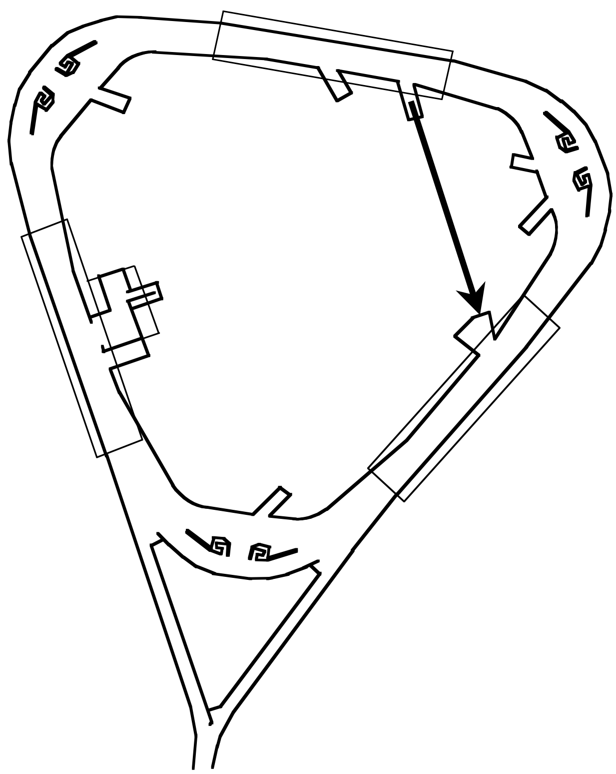
System	Debuncher Horizontal	Debuncher Vertical	Debuncher Momentum
Pickup location	D10	D10	D10
Kicker Location	D30	D30	D30
# of pickup pairs	128 4 tanks with 32 each	128 4 tanks with 32 each	256 all of the H&V pickups
Bandwidth	4-8 GHz	4-8 GHz	4-8 GHz
# of TWTs	16	16	32
# of kicker pairs	128	128	256
typical operating power	1,000 watts	1,000 watts	1,500 watts

Table 1, Debuncher Cooling Systems

1. Debuncher Betatron

The Debuncher Betatron systems reduce the transverse emittances of beam in the Debuncher so that it will fit into the Accumulator. Each system presently reduces the emittance from 17 pi-mm-mrad to 4 pi-mm-mrad in 1.5 seconds. The bandwidth of these cooling systems is 4-8 GHz. A total of 128 pairs of pickup electrodes are spaced over six vacuum tanks located in straight section D10 for each system. Because the pbar intensity in the Debuncher averages only 6-9x10^7 particles, the coherent signal derived from the beam needs to be maximized. In addition to summing the signal from four tanks of pickups, the electrodes as well as the preamplifiers are cooled with liquid helium. This serves to reduce the thermal noise, which would contribute to the heating term. Unwanted signals are also removed by the use of correlator Bulk Acoustic Wave (BAW) notch filters. These filters notch out unwanted thermal noise at harmonics of the revolution frequency and between betatron sidebands, leaving only the signals from the betatron sidebands as signals, which are amplified by the TWTs and applied to the kickers. By increasing the signal to noise ratio, less TWT power is produced as noise that would heat the beam leaving more power to cool the beam.

AP30AP50AP10Figure 5.8 Location of Debuncherstochastic cooli



The four kicker tanks are located in straight section D30 (see figure 5-8). Due to the length of the pickup and kicker arrays and the need to keep the proper phase advance between the pickups and kickers, the 4 tanks are separated by 180° of betatron phase advance and combined with a 180° hybrid. The 128 kicker electrodes in each plane are powered by 16 TWTs at an average total power of about 1000 Watts per plane. The LCW-cooled TWTs are mounted directly on the kicker tanks.

2. Debuncher Momentum

Antiprotons that circulate in the Debuncher have their momentum spread further reduced after bunch rotation and adiabatic debunching by means of a momentum cooling system. This cooling system was added in 1989 and uses the same pickup and kicker electrodes as those in the Debuncher betatron systems. Instead of using the signals from the pickups in the difference mode, however, the sum signal is gathered. Similarly, the signal applied by the kickers to the beam is in the sum mode. The frequency range of this system is 4-8 GHz. This system currently reduces the Debuncher Δp/p (momentum spread) from ~ 0.30% to < 0.17% in 2.4 seconds

All of the Debuncher transverse pickup and kicker electrodes are used for the momentum system – the kickers are driven with both momentum and transverse signals. 32 TWTs dedicated only to momentum cooling, again mounted on the kicker tanks, provide a nominal 1,500 watts of longitudinal cooling. This system also has a notch filter that provides the gain shaping necessary to do momentum cooling.

System	Stack Tail Δp	Core 2-4 βtron	Core 4-8 βtron	Core 2-4 Δp	Core 4-8 Δp
Pickup location	A60	A10	A10	A60	A20
Kicker Location	A30	A30	A30	A30	A50
# of pickup sets	256 at +15.7 MeV (2 tanks with 128 each) 48 at –3.8 MeV 16 at –22.7 MeV	16 planar pairs each plane	32 planar pairs each plane	16 at core orbit 16 at central orbit	32
Bandwidth	2-4 GHz	2-4 GHz	4-8 GHz	2-4 GHz	4-8 GHz
# of TWTs	32 sum 4 delta	1 horizontal 1 vertical	1 horizontal 1 vertical	1	2
# of kicker pairs	256 with 64 delta kicker pairs (half vertically half horizontally oriented)	16 each plane	32 each plane	32	64
typical operating power	1,000 watts	50 watts each plane	20 watts each plane	40 watts	0-10 watts

Table 2, Accumulator Cooling Systems

3. Accumulator Stack Tail Momentum

After antiprotons have been injected into the Accumulator, the particles must be decelerated roughly 150 MeV to reach the core. The first 60 MeV of deceleration is handled by ARF-1 while the final 90 MeV is accomplished by the 2-4 GHz stacktail momentum system. Because an RF bucket displaces beam that it passes through, it was not possible to use an RF system to decelerate beam the full 150 MeV to the core.

All of the stacktail pickups are located in the A60 high dispersion region and are subdivided into three separate arrays called the +15.7 MeV (leg 1), –3.8 MeV (leg 2) and –22.9 MeV (leg 3 or compensation leg) pickups. Figure 5.9 shows the relative positions of the stacktail and core momentum pickups. The pickup names identify the part of the stacktail for which the particular

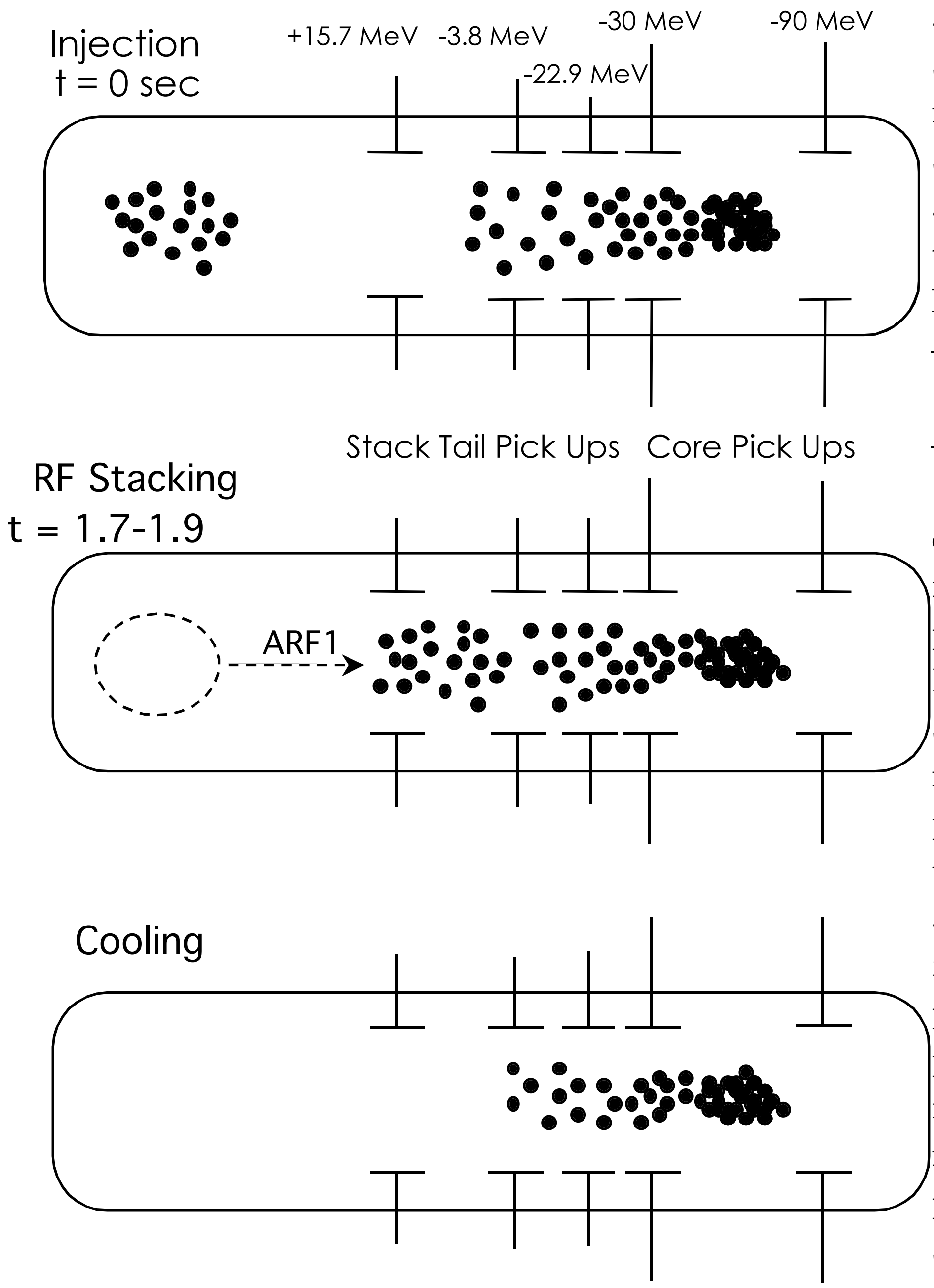
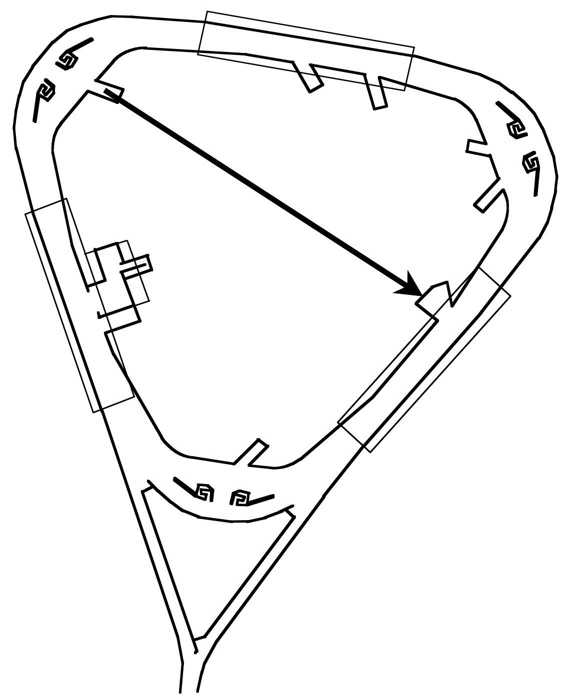


Figure 5.9 Stacktail and core momentum pickup location

pickup array is most sensitive relative to the central orbit of the Accumulator. The stacktail extends from about +30 MeV where ARF1 deposits beam to the edge of the core at about -30 MeV. The +15.7 MeV pickups are most sensitive to beam that is 15.7 MeV higher in energy than beam located on the central orbit. The shift in position at the pickup is due to the dispersion at that location. A difference in energy results in a primarily horizontal position shift (there is very little vertical dispersion in the Accumulator). A notable difference in the three arrays is in the number of pickup elements each one contains. The +15.7 MeV pickups are made up of 256 individual pickup electrode pairs divided evenly between two different tanks. The –3.8 MeV pickups, made up of 48 electrodes, and the –22.9 MeV pickups having only 16 electrodes, are located inside another tank. Figure 5.10 shows the location of the pickup tanks in the A60 straight and the kickers in the A30 straight section.

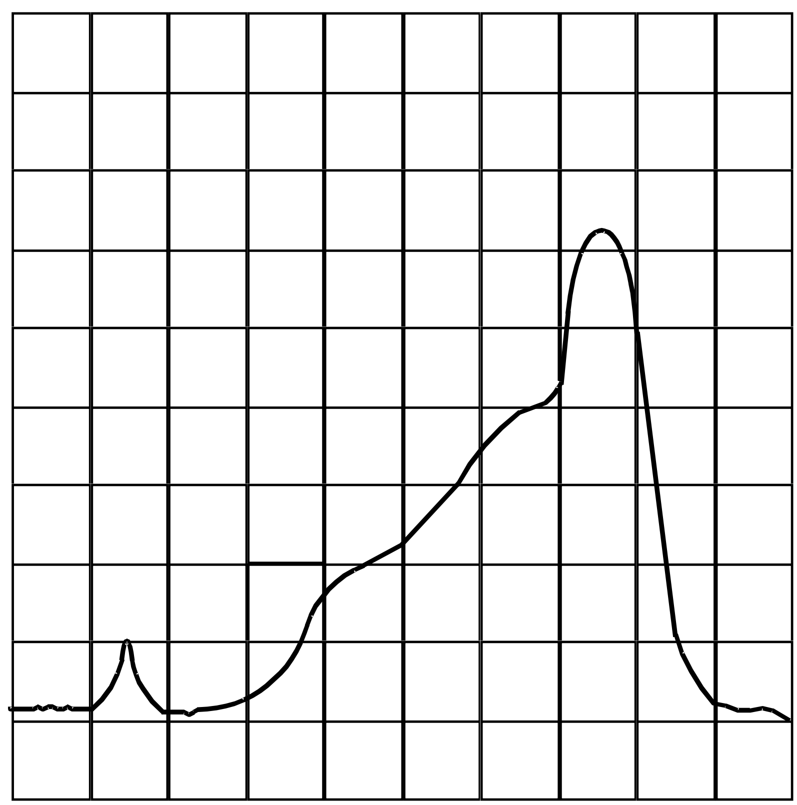
AP30AP50AP10Figure 5.10 Location of Accumulatorstacktail mo



To understand why there are so many pickup electrodes at +15.7 MeV and so few at –22.9 MeV, consider how beam is distributed in the stacktail. At the deposition orbit, the point where ARF-1 drops off the beam, there is a relatively small amount of beam for the +15.7 MeV electrodes to detect. For the stacktail system to work effectively, a certain amount of beam signal must be detected above the background noise. Thermal noise from the pickups is reduced by cooling parts of the pickup assemblies to liquid nitrogen temperature. To achieve the proper amount of beam signal from the +15.7 MeV array, it is necessary to have a large number of pickups. The –22.9 MeV pickups, on the other hand, are located much closer to the core where there is considerably more beam. Sixteen electrodes are adequate to produce a reasonable signal to noise ratio.

The signals coming from the pickup arrays are manipulated by the stacktail electronics and provide the phase and gain characteristics necessary to effectively momentum cool the beam in the stacktail while minimizing effects on beam in the core. The system gain changes nearly exponentially across the stacktail, and is highest where ARF-1 drops beam off and lowest at the edge of the core. Because of this, the high-energy beam arriving at the edge of the stacktail moves very rapidly away from the deposition orbit. It is important for the stacktail system to have this feature since any beam remaining near the deposition orbit will be RF displaced into the injection kicker shutter when ARF-1 pulses on the next stacking cycle. Low energy beam on the core side of the stacktail moves very slowly and tends to "pile up" against the core, giving the stacktail its characteristic shape which is illustrated in figure 5.11.

Start Freq 79.22200001 MHzStop Freq 79.24900001 MHzAccumulator Longitudinal Profile08/03



Transverse kicks induced by the stacktail momentum system, mostly due to imperfect hybrids and kicker misalignment, lead to betatron heating of the beam in the stacktail and core. This is partially overcome in the stacktail system by applying a small part of the signal from 64 sets of the kicker electrodes in the difference or delta mode (recall that momentum pickups and kickers are normally in the sum mode). The first and last kicker tanks in the A30 straight section are stacktail tanks used as "delta kickers". These tanks were selected because they are nearly 90° out of betatron phase with each other. Half of all of the stacktail momentum kicker electrodes are oriented horizontally and the other half are oriented vertically. Since the signal is applied in sum to each electrode pair, the particles passing between the plates see a longitudinal field. The delta kickers have the difference signal applied, resulting in a transverse kick to the beam. The delay and attenuation values for the delta kickers are calculated using network analyzer beam measurements to offset the heating induced by their longitudinal counterparts.

4. Core Momentum

The Core momentum cooling systems keep the antiproton core contained by decelerating high-energy particles and accelerating low energy particles. There are two core momentum systems currently in use. The original 2-4 GHz system, which has its pickup tank in the A60 high dispersion straight section and kickers in the A30 area (see figure 5.12), and the 4-8 GHz system added in 1989 which includes a pickup tank in the A20 section and a kicker tank in A50 (see figure 5.13). The 4-8 GHz system was first used by E760 because of its ability to provide a smaller momentum spread and decreased cooling time. Another important advantage of this system for E760 (and now E835) was that the pickup arrays could be remotely moved so they could be centered on beam on the central orbit. During data taking, most experiments maintain the stack at the central orbit of the Accumulator rather than at the low-energy side of the Accumulator as is the case during stacking operation.

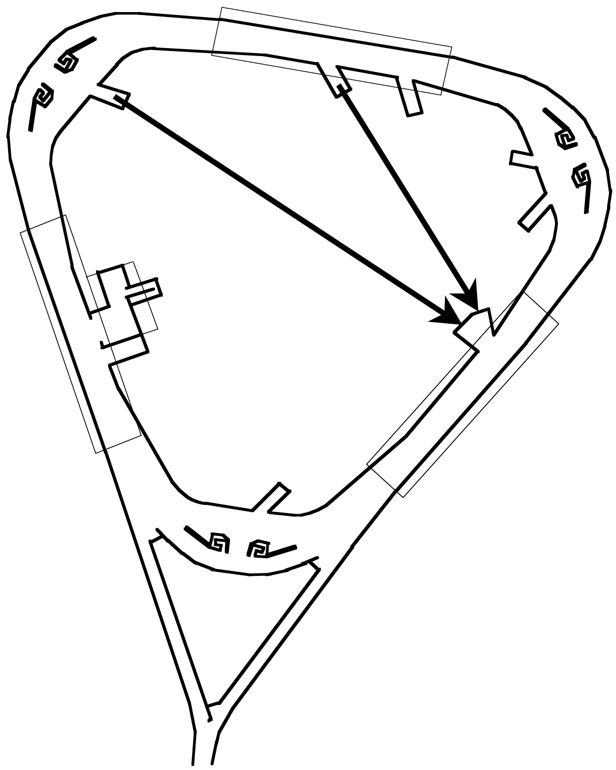
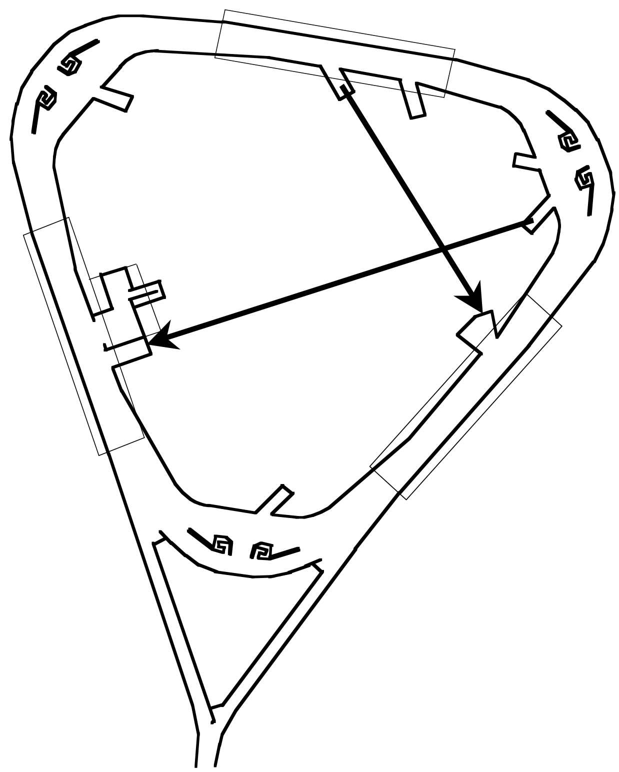


Figure 5.12 Location of Accumulator core2-4 GH

The 4-8 GHz core momentum system was later pressed into service during the 1992-93 Collider run to provide a denser core from which to unstack antiproton bunches. Typically the 4-8 GHz core momentum system was kept off during stacking and the beginning of the shot set-up. The system was then turned on approximately midway during the set-up to provide time for the core to narrow and then stabilize with this system on. The two core momentum systems are stand-alone systems, so it is possible for them to cool the core to different momenta. The 4-8 GHz core momentum system is more efficient than the 2-4 GHz core momentum system (at the expense of the momentum range over which it can cool) because of the greater bandwidth of the 4-8 GHz system. Normally the pickups of the 4-8 GHz system are positioned so that both systems are cooling to the same revolution frequency (at this time only the 4-8 GHz pickup arrays can be moved). With the upgrade of the stacktail momentum system to 2-4 GHz, the 4-8 GHz core momentum system will carry most of the cooling load in the future. The 2-4 GHz core momentum system has not been decommissioned, however.

AP30AP50AP10Figure 5.13 Location of Accumulator core4-8 GH



5. Core Betatron

There are both 2-4 GHz and 4-8 GHz transverse cooling systems made up of a horizontal and vertical system each. These systems exist to control the transverse emittances of particles in the core. Pickup tanks are located in the A10 low dispersion straight section, an area where any sensed position error will be due to transverse rather than longitudinal (momentum) oscillations. The kickers are in the A30 straight section.

Originally horizontal and vertical core betatron cooling systems were operated in the 2-4 GHz bandwidth. Both systems were then upgraded to operate at 4-8 GHz by replacing the pickup arrays (which were also an improved planar loop design) and installing new kicker tanks. Although the 4-8 GHz transverse systems cooled the core more efficiently, they did not extend their domain into the edge of the stacktail as the 2-4 GHz systems had. Also, the response of the 4-8 GHz systems dropped off more rapidly at higher frequencies than anticipated. The effective bandwidth of the 4-8 GHz systems was only slightly better than the 2-4 GHz systems (not the expected doubling). In the spring of 1995 the 2-4 GHz systems were recommissioned by replacing half of the planar array pickups that had formerly been used by the 4-8 GHz systems and using the existing kicker tanks in A30 (the 2-4 GHz core betatron and core momentum systems share the same kickers). Normally the 2-4 GHz and 4-8 GHz transverse systems are run simultaneously. The plan is to eventually build equalizers for the 4-8 GHz systems to compensate for the loss of response in the higher frequencies.

References

1) S. van der Meer, An Introduction to Stochastic Cooling, AIP Proceedings 153, SLAC Summer School, 1985; Fermilab Summer School, 1984; pp. 1628-1649.

2) A. V. Tollestrup and G. Dugan, Elementary Stochastic Cooling, unpublished

3) John Marriner, David McGinnis, An Introduction to Stochastic Cooling, AIP Conference Proceeding #249 VI, 693-761 (1990)

4) D. Möhl, G. Petrucci, L. Thorndahl, S. van der Meer, Physics and technique of stochastic cooling, Phys. Reports 58 (1980) 73-119.

5) Robert L. Shrader, Electronic Communication - fourth edition, McGraw-Hill Book Company.

6) D. Möhl, Stochastic Cooling for Beginners, PS/LEA/Note 84-12.

7) Design Report Tevatron I Project, September 1984, Fermilab.

8) Conversations with Ralph Pasquinelli.

9) D. Möhl, CERN Internal Report, CERN 87-03 V2:453-533 (1987)

10) Bisognano, Leeman AIP Conference Proceeding #87 Fermilab Summer School on Accelerator Physics 1981

11) D.A. Goldberg, G.R. Lambertson, Dynamic Devices; A Primer on Pickups and Kickers, AIP Conference Proceeding #249 VI, 537-600 (1992)